Recent Light Extraction Development in OLED

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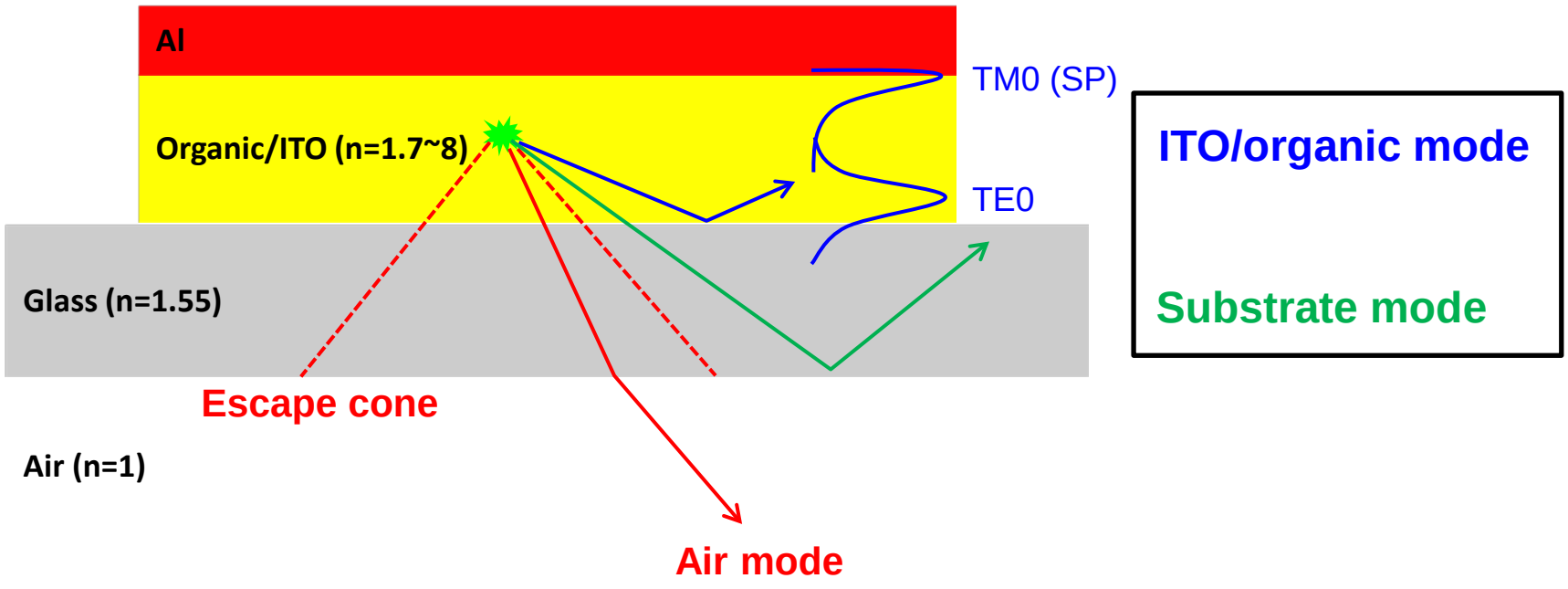
Outcoupling Efficiency (χ_{out})

- Internal quantum efficiency (η_{int}) : ~ 100%
- External quantum efficiency (η_{ext}) : **~25%**

$$\eta_{ext} = \chi_{out}\eta_{int}$$

  - ITO/organic waveguide mode : ~50%
  - Substrate mode : ~25%
  - **Air(outcoupled) mode : ~25%**

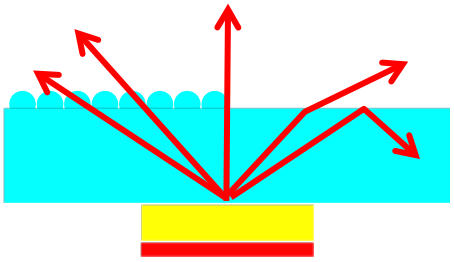
χ_{out} **: ~25%**

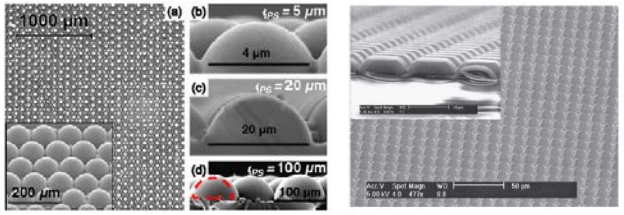


Outcoupling for substrate mode

◆ Outcoupling techniques

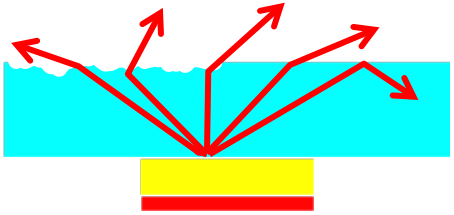
- Microlens array





Möller, J. Appl. Phys. 91 (2002)

- Substrate roughening



Chen, Opt. Express 18, 37 (2010)

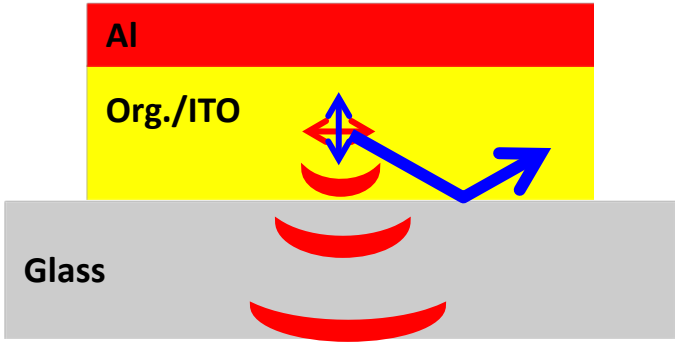
1.5~1.8 times enhancement with convenient and low cost fabrication

Out-coupling for thin film guided mode

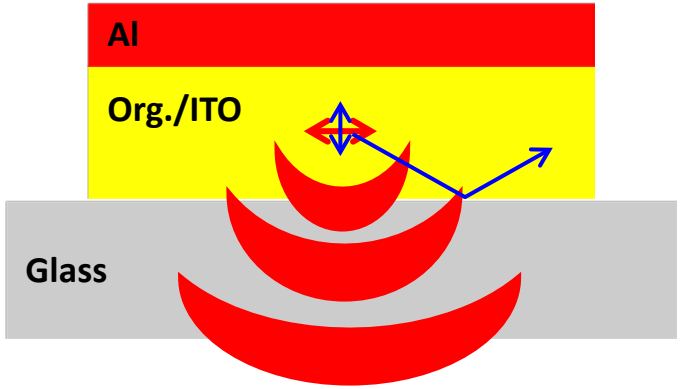
Other concepts of outcoupling techniques

- **Horizontally oriented emitter**
  - Isotropic dipoles

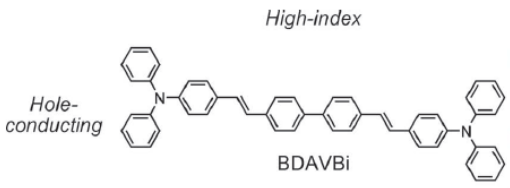
↕ vertical ↔ horizontal

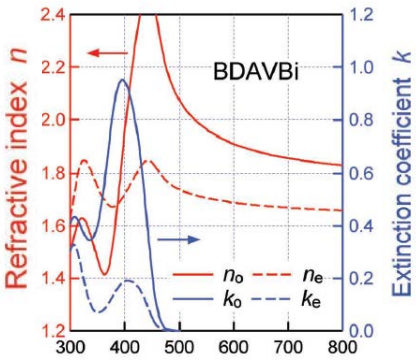


  - Horizontally-oriented dipoles



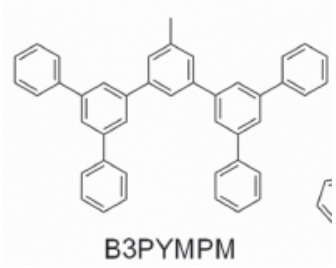
- D. Yokoyama et al, Adv. Funct. Mater. 24 (2012)

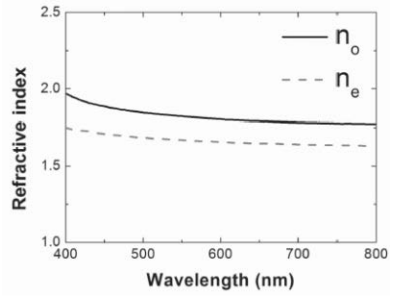




➡ More horizontally-oriented materials

- Kim et al, Adv. Funct. Mater. 23 (2013)



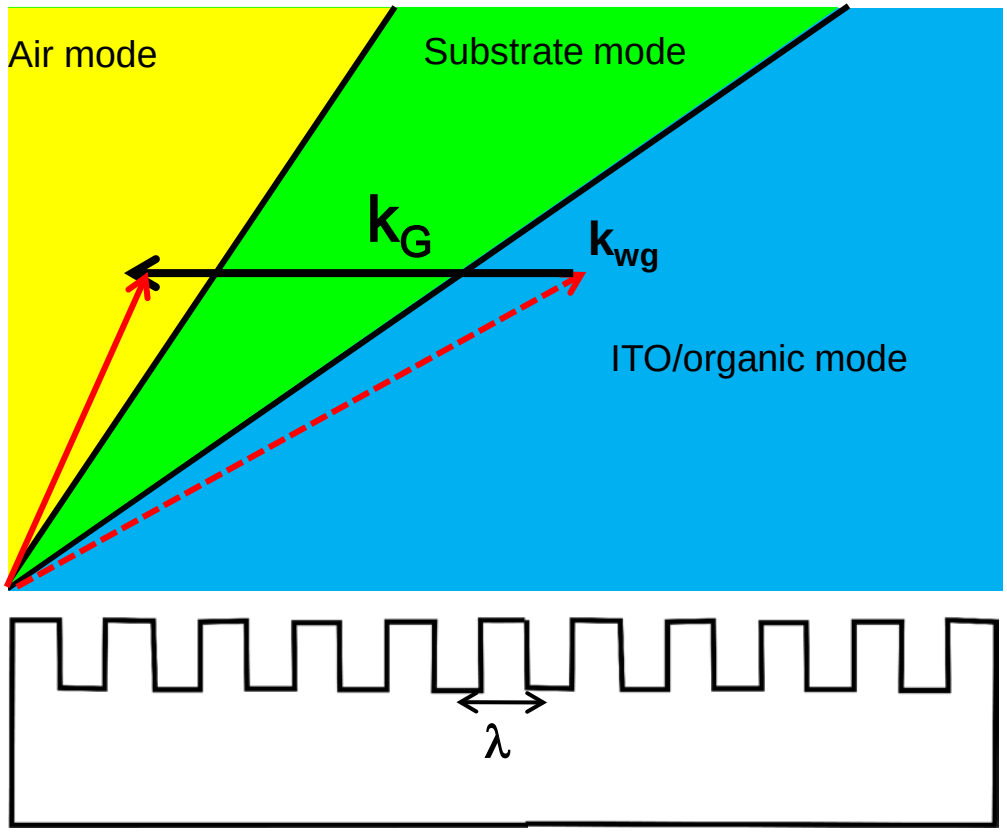


➡ Horizontally oriented emitters by **non-isotropic matrix of B3PYMPM** in emitting layer

➡ Exceeding EQE of 30%

Outcoulping for wave-guided mode :Corrugated OLEDs

◆ **Schematic dispersion curve in OLED**



◆ **Diffraction grating equation**

$$k_{//} = k_o \sin\theta = k_{wg} \pm mk_G$$

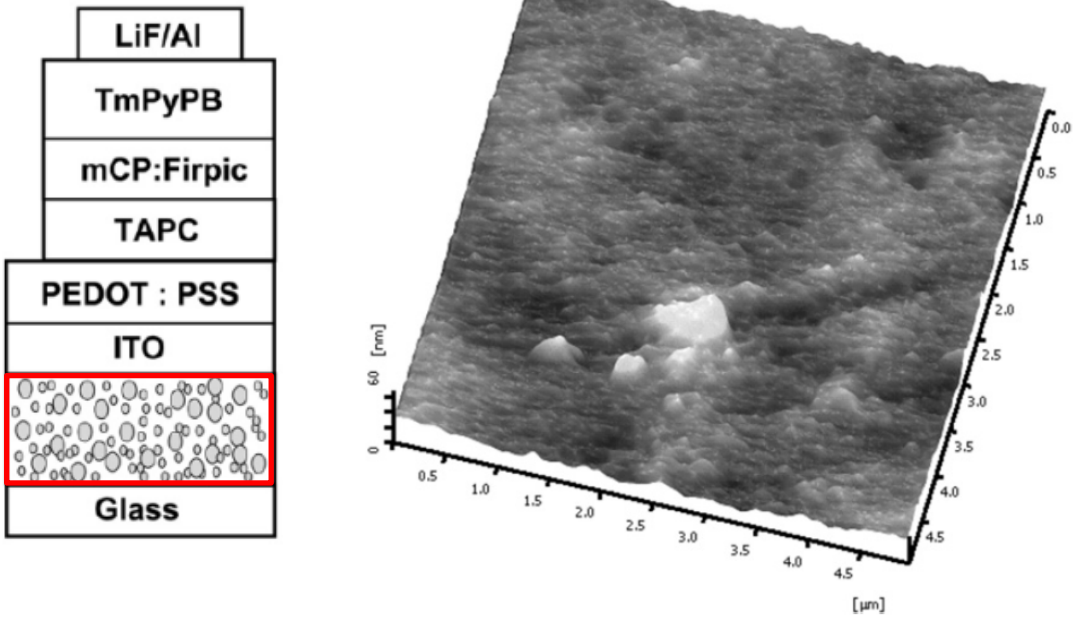
$$k_G = 2\pi / \lambda_G$$

k_o : wavevector in free space
k_{II} : wavevector of in-plane component of k_o
θ : angle of emitted light with respect to the surface normal
k_G : wavevector of grating
M : integer
λ_g : period of grating

- Key to control grating vector/periodidicity of the grating structure
- 0.3~ 1 um periodicity with 40~100 nm of depth

Outcoupling for wave-guided mode

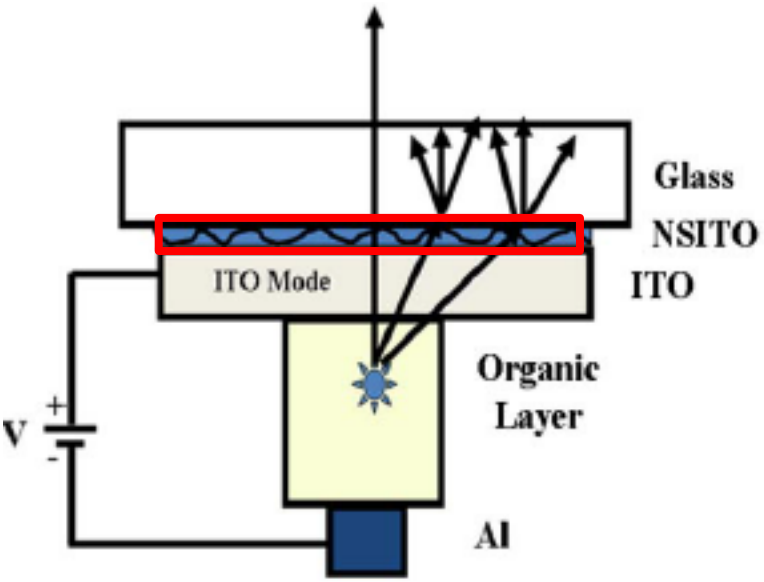
◆ **Internal scattering layer** - C. Chang et al, Org. Electron.13, 1073 (2012)

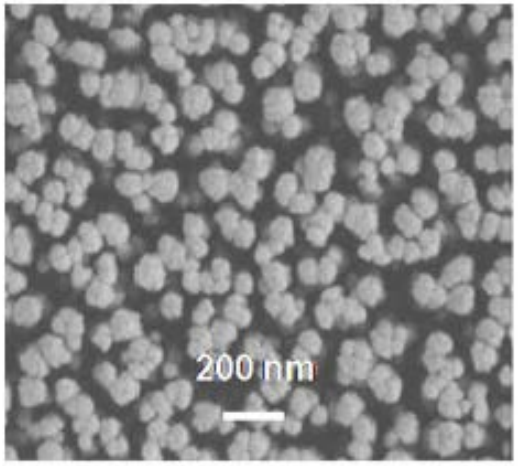


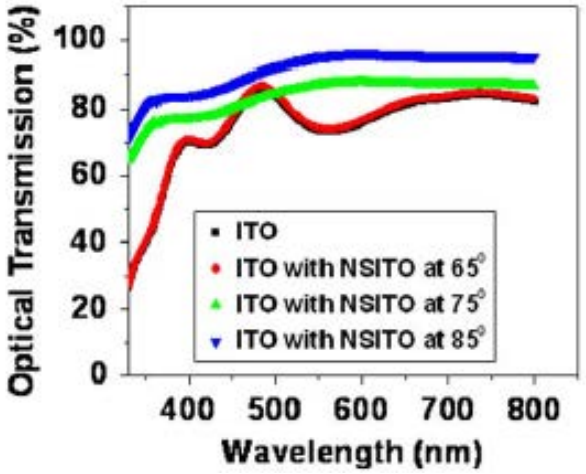
- Scattering layer : : transparent photoresist (n=1.52) + TiO_2 particles
  - ➡refractive index : n=1.5~1.9
  - ➡still high transparent ~85%
  - ➡2 times enhancement in EQE

Outcoupling for wave-guided mode

◆ **Scattering ITO layer** - A. Kumar et al, Opt. Lett. 37 (2012)



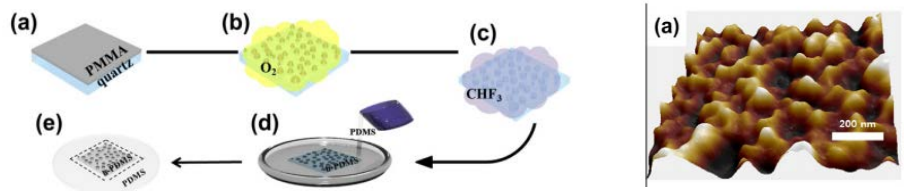




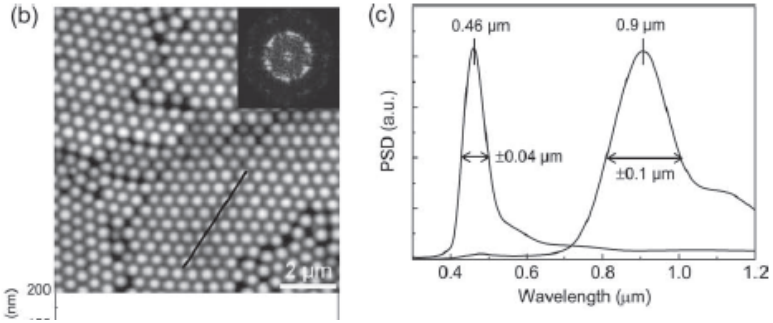
- **Scattering porous nanostructured ITO**
  - ➡ Glancing angle deposition method by RF sputter
    1. Scattering media formed by porous/n-ITO particles
    2. Index varies from 1.2-1.9 depending on the deposition angle
    3. 80% enhancement in light output

Other similar works – different fabrication methods

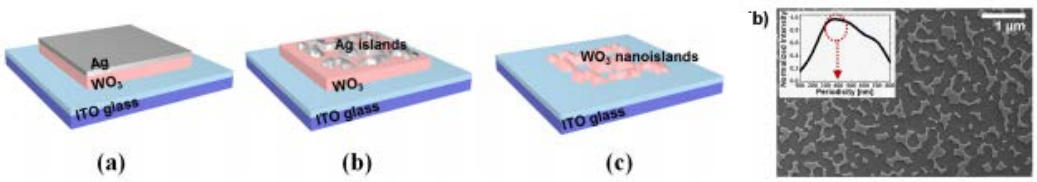
- S. Shin et al, Org. electron. 14 (2013)
  - ◆ **Dry-etching patterning**



- W. Koo et al, Adv. Funct. Mater. 22 (2012)
  - ◆ **Defective HCP grating**

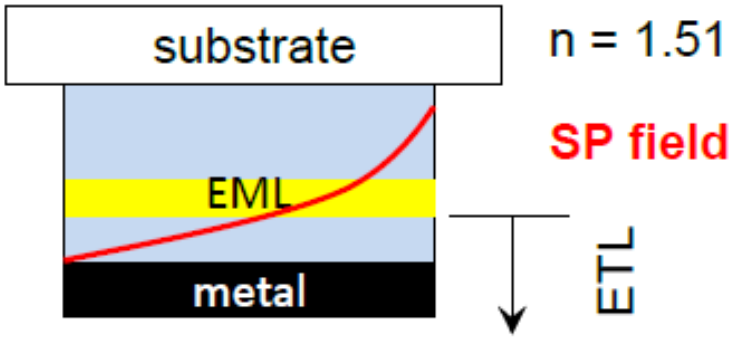


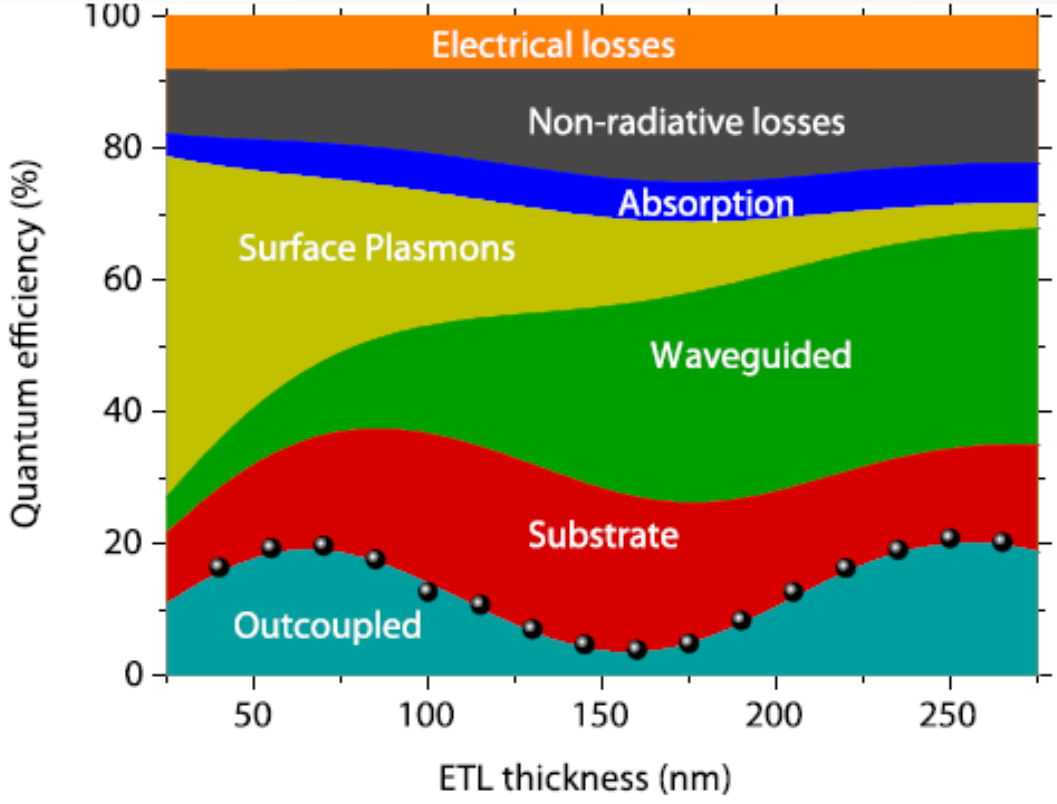
- J. Kim, Opt. Express. 5 (2013)
  - ◆ **Island-Ag mask & wet etching**



Optical modes – device structure dependence

Appl. Phys. Lett. 97, 253305 (2010)



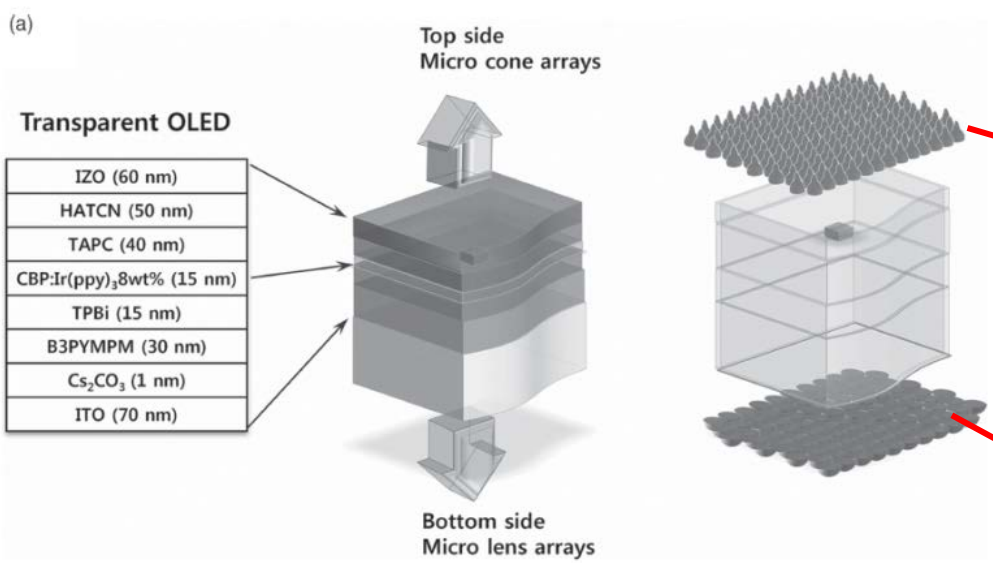


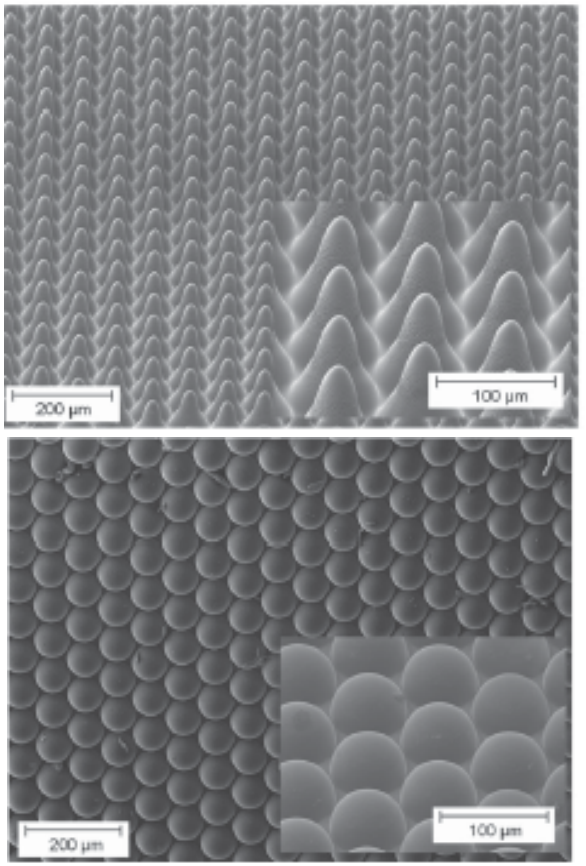
Other concepts of outcoupling techniques

◆ Metal-free both side transparent electrodes

- Kim et al, Adv. Mater. 25, 3571 (2013)

Structure & SEM of electrodes





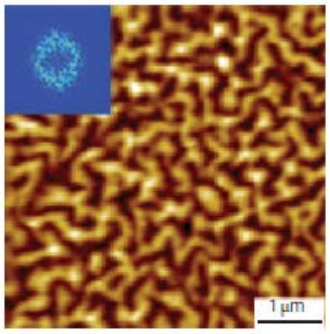
- **Metal-free OLED with a high index**
  - ❖ A high index light extraction layer deposited on the top electrode with a bottom microlens array
  - ❖ An EQE of 55% was achieved @ 1000 nits

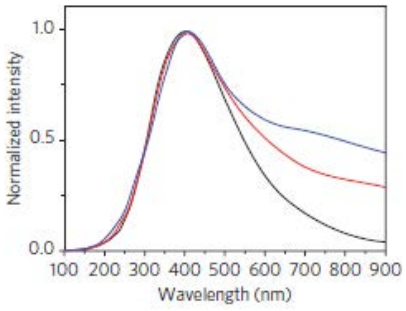
Outcoupling for wave-guided mode :Corrugated OLEDs

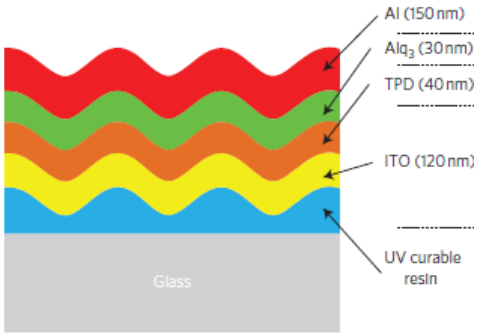
◆ OLED on buckle structure

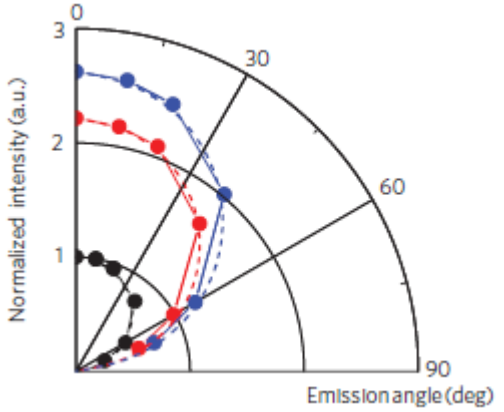
- **W. Koo, Nature photonics 21 (2010)**

- Grating structures with **broad distribution of periodicity**
  1. All wavelength extraction met by Bragg diffraction law
  2. Still close-Lambertian distribution
  3. 2.2 times enhancement in current efficiency

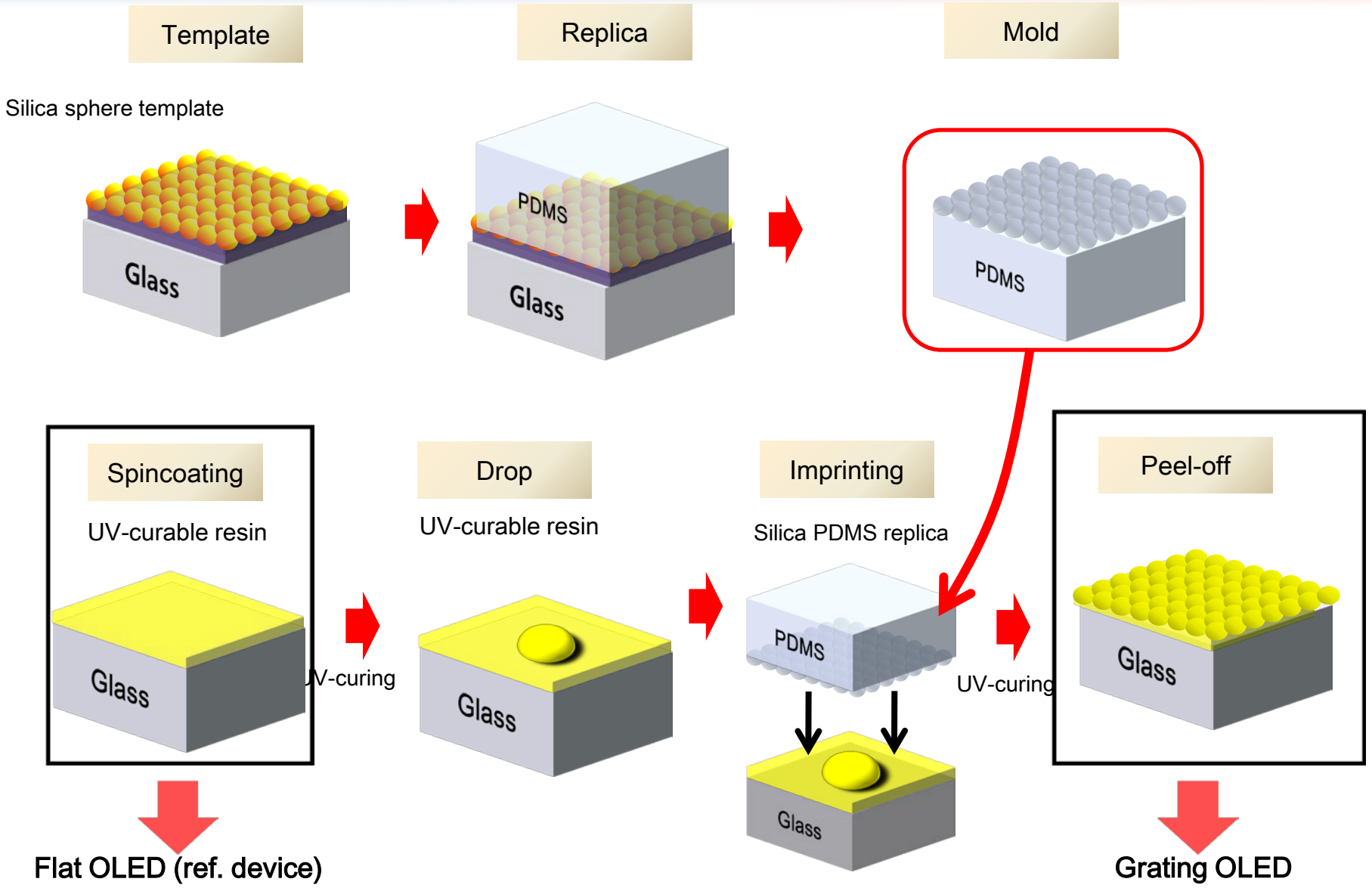




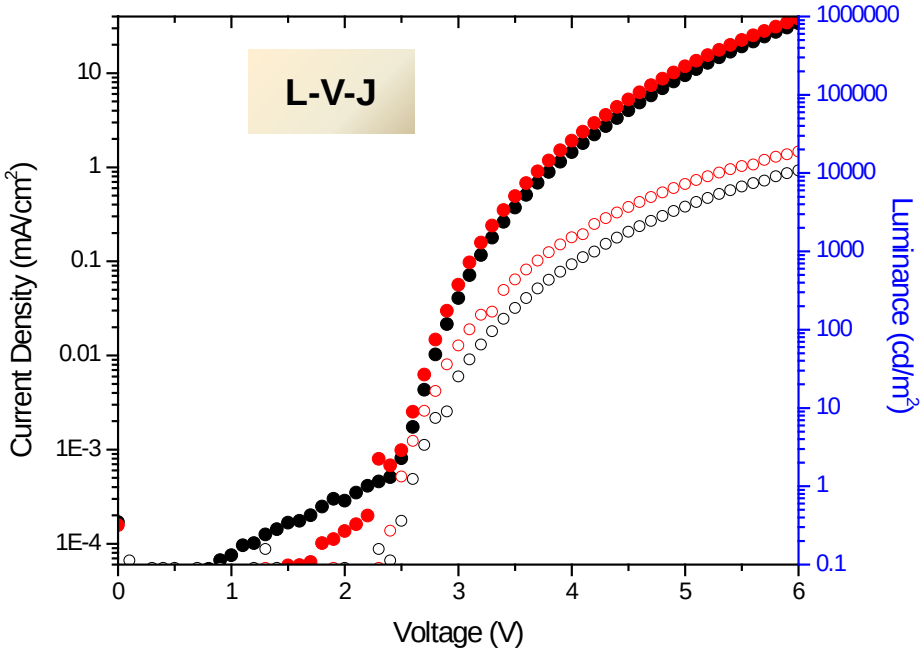


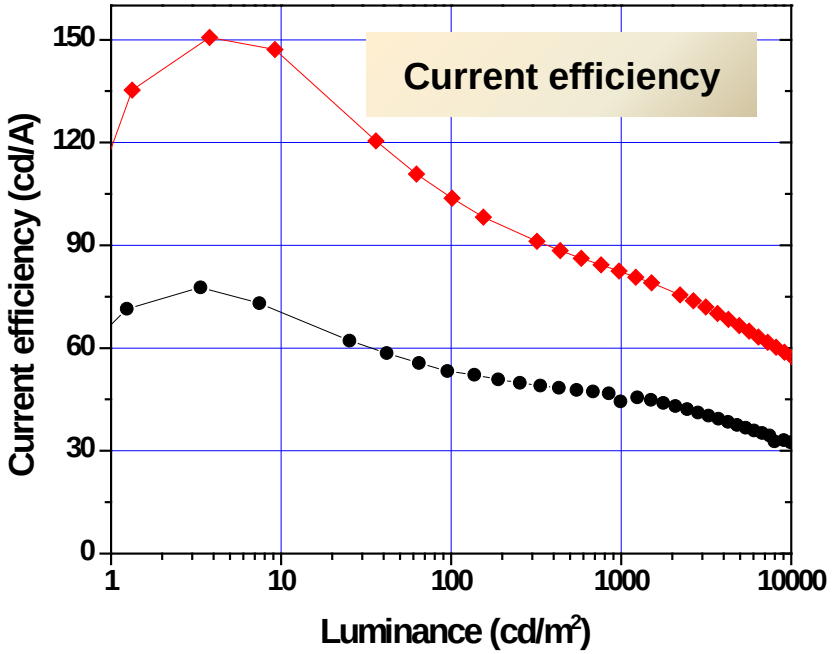


Corrugated structure fabrication



High efficiency $Irppy_3$ devices w/ grating

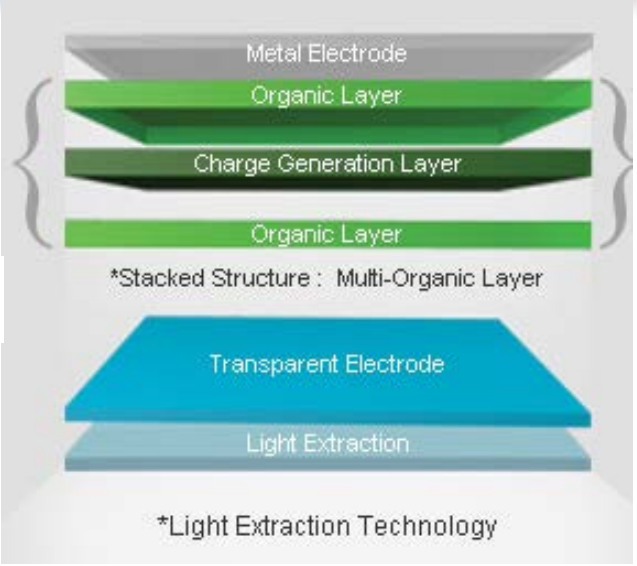




- Grating : 74 cd/A and Ref : 48 cd/A at 2000 cd/m2
  - ➢ 55% enhancement in current efficiency
    - ✓ At low luminance, current efficiency is more than 2X enhanced

Latest OLED lighting product development

LG Chem



- Commercial 80 lm/W OLED with outcoupling for waveguide mode in 2013

http://www.lgchem.com/global/green-energy/oled-lighting

Panasonic

Figure: Panasonic - High efficiency white OLED

- 114 lm/W OLED in 2013
- **Built-up Light Extraction Substrate (BLES)** 50% EQE

http://www.osadirect.com/news/article/970/

Going forward….

- EQE approaching 70% is possible
- Low-cost manufacturing light extraction schemes are needed for SSL

Thank you for your attention